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Worldwide Activities on the Reduction of Occupational Exposure at Nuclear Power Plants

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ABSTRACT

This report is based on analysis of an informational data base set up at the Brookhaven National Laboratory ALARA Center. It is part of a project sponsored by the U.S. Nuclear Regulatory Commission to monitor and evaluate research on dose reduction at nuclear power plants in the U.S. and abroad. The main benefits to be expected from reducing occupational exposures are highlighted in the report, the chief causes of elevated doses are identified, and effective approaches to minimize radiation exposures are proposed.

A wide range of research activity is covered, including plant chemistry, cobalt reduction techniques, stress corrosion cracking, decontamination, remote tools and devices, and robotics. Advanced reactors, which are designed for low radiation exposures, are examined, and health physics technology programs which have been effective in reducing occupational exposure at various utilities are discussed.

The highlights of the programs on dose reduction conducted by a number of countries are described, and comparisons are made of the collective occupational radiation dose equivalents for selected countries. The short and long term trends such studies are pointing to are evaluated.

It is concluded that the efforts to improve dose reduction, both in the U.S. and abroad, remain in a healthy state but require continuing encouragement and further development.

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1. EXECUTIVE SUMMARY

The Nuclear Regulatory Commission tasked the Brookhaven National Laboratory to review and evaluate the ongoing efforts in the U.S. and abroad to reduce occupational radiation exposure at nuclear power plants. Of interest are not only the research and development programs but also the substantial amount of work being done in the area of health physics technology. A data base containing information on over 400 projects has been set up at Brookhaven as a part of this study. The present document is an interim report on the project. In it we examine the effectiveness of these activities, look at trends, and indicate areas where future effort is likely to be productive.

Reduction in occupational exposure to radiation at nuclear power plants is desirable not only because it affects the health and safety of plant personnel but also because it enhances the safety and reliability of nuclear power plants, making their operation more efficient and economical.

The primary source of occupational exposures at power plants is activation products deposited on out-of-core surfaces. These products elevate radiation fields throughout most of the plant, leading to high doses during maintenance and inspections. Other major causes are additional maintenance needed to service plants as they age, and inspections, modifications, and retrofits required to increase plant safety.

Collective radiation dose equivalent in nuclear plants in the U.S. increased to an average of 791 person-rem per reactor per year in 1980. Since then the trend is down, reaching 460 person-rem per reactor per year in 1986. Research in dose reduction and the health physics technology activities are partly responsible for this improvement. The trend is likely to continue in the near future, since the lessons learned from dose reduction research are just beginning to be applied. However, when compared to other countries with major research programs on dose reduction, the collective dose in the U.S. is still among the highest. For example, the doses are higher by an order of magnitude compared to the Nordic countries. Moreover, closer examination of the data shows some ambiguity in the downward trend in dose (see section 3.3). Thus, there is considerable room for further reductions in the U.S. collective doses.

Tables 1.1 and 1.2 summarize the impact on collective occupational exposures of the principal techniques being employed to reduce occupational radiation exposures. These techniques are in various stages of research, development and implementation. The conclusions based on the tables are necessarily subjective, although every effort has been made to be as objective as possible.

In these tables the impact has been split into three time frames. Thus, "short term" is defined as within the next 7 years. During this period a large number of existing plants in the U.S. will continue in service and some new plants, still of older design, will come on-line. Towards the end of this period a few plants incorporating new design concepts will come on-line in other countries. "Intermediate term" is defined as the period from 7 to 20 years, when a number of U.S. plants are likely to be refurbished, and some old plants may be retired. Additionally, plants based on advanced designs may be ordered, although the effect of the new plants on the total collective occupational exposure in the U.S. is not likely to be substantial. A number of new plants will come on-line abroad during this period. "Long term" is defined as the period after 20 years, when it is expected that newer plants based on more advanced technology will be operating in the U.S., and the older plants will have been retired and possibly decommissioned. The effect of the advanced-design plants is likely to be very significant on occupational radiation exposure during this time period. Some of the techniques that played a key role in the first phase will then be providing diminishing returns and some of the problems that afflict present day power plants will have been solved. For example, component decontamination, which should reduce dose significantly in the early phase, might very well be much less important in subsequent phases because occupational radiation exposure advanced plants will not require frequent decontaminations, and also because full system decontamination processes should be available. The decontamination processes that produce low volumes of waste, should play an important role in the intermediate phase. They may be less important in the last phase since the occupational radiation exposure advanced plants may well generate relatively little waste. For these reasons, the estimate of the potential impact in the two tables is to be interpreted as relative to the annual collective dose at the beginning of the appropriate period and in the context of the conditions prevailing at that time.

Table 1.1: Potential Impact of Radioactive Source Reduction Techniques on Nuclear Power Plant Collective Occupational Exposures

	Potential Impact on Collective Dose[1]			
Technique	Short term[2]	Intermediate term[2]	Long term[2]	Remarks
Cobalt reduction	low	medium	high	largest impact on new plants
Pre-conditioning	low	medium	medium	for new plants and replaced components
Water chemistry	medium	medium	medium	cost-effective technique
Component decontamination	medium	low	low	more effective for older plants
Full system decontamination	-	medium	low	critical path savings
Low waste decontamination processes	-	medium	low	low waste handling costs
Advanced reactor designs	-	medium	high	very large source reductions possible

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[1] Relative to the annual collective dose at the beginning of the appropriate period.

[2] Short (<7 years), intermediate term (7-20 years), long term (>20 years)

Table 1.2: Potential Impact of Exposure Time Reduction Techniques on Nuclear Power Plant Collective Occupational Exposures

	Potential Impact on Collective Dose[1]			
Technique	Short term[2]	Intermediate term[2]	Long term[2]	Remarks
Improved materials	low	medium	medium	significant for component replacement and new plants
Control of IGSCC[3] of BWR piping	medium	medium	low	important for present BWRs
Control of PWR steam generator tube corrosion	medium	medium	low	important for present PWRs
Remote tools	low	low	medium	significant for new and standardized plants
Robotics	low	medium	medium	need rugged, reasonably priced devices
Operational and maintenance techniques	low	medium	medium	very cost-effective for dose reduction
Advanced reactor designs	-	medium	high	offer new possibilities for remote tools,robotics etc.

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[1] Relative to the annual collective dose at the beginning of the appropriate period.
[2] Short (<7 years), intermediate term (7-20 years), long term (>20 years)
[3] Intergranular Stress Corrosion Cracking

Many exposure reduction initiatives are inter-related. Implementation of one initiative can significantly reduce the benefit of another Because of this inter-relation, some initiatives, while providing major benefits, can even cause an increase in exposure. For example, with current chemistry PWR S.G. channel head dose rates might be as high as 20 rad/h. If a major retubing effort were to be planned, a decontamination might reduce the dose rates to 3 rad/h. On the other hand, if a plant with improved chemistry has channel head dose rates of 7 rad/h, the decontamination effort may no longer be cost effective.

Because of this inter-relationship improvements in some areas, for example cobalt reduction and chemistry control, may reduce the need for costly research and development work in other areas, such as full system decontamination. Clearly, there is a need for an overall strategy in the effort to reduce dose.

Research projects designed to reduce plant source terms have their major thrust in three different areas: to minimize sources of cobalt in the primary systems of reactors; to precondition primary system surfaces so that release of corrosion products is reduced and plating out of activation products is mitigated; and to use advanced water chemistry to control transport, deposition and resuspension of crud. These techniques are discussed in section 4.1.

Research and development work to remove contamination is presently directed at dilute decontamination processes which appear to be very successful for both PWRs and BWRs. With concerns regarding corrosion largely resolved, attention is now being focussed on reducing process time and minimizing radwaste. The next major step is likely to be decontamination of the entire reactor primary system, both with and without the fuel in place. Field tests underway at a BWR plant to prove the viability of the concept of full system decontamination with the fuel in place may also have some application for PWRs although for these plants decontamination of the full reactor primary cooling system with the fuel removed appears to be the more cost-effective approach. Lastly, development of decontamination processes that produce very low volumes of radioactive waste may be possible. More detailed information is provided in section 4.2.

Research to improve the reliability of components has almost overcome the BWR problem of intergranular stress corrosion cracking of primary system piping. Remedies to reduce stress and improve the chemical environment have been developed. The problem of corrosion in PWR steam generator tubes also has been largely mitigated, both for operating plants and those under construction. Several components and materials of high performance and reliability have been developed; others are in various stages of development. Additional information is given in section 4.3.

Remote tools and devices are being used more frequently. Some of these have yet to be proven effective and in some cases their cost-effectiveness is dependent on plant related circumstances. Reference 1 examines the cost-effectiveness of a number of devices. Multistud tensioners for reactor pressure vessel heads are used at several foreign utilities and some U.S. plants. In Japan, automatic inspection equipment was developed and automatic refueling and control rod drive handling machines are used routinely Control rod drive handling machines, which are believed to be more economical and easier to backfit, have also been designed and deployed in US power plants. Some steam generator tasks are accomplished by remote operation or by automatic machinery in the U.S. and abroad. Promising robotics devices are undergoing field tests, and a few with success. More details are given in section 4.4.

Cooperative studies, involving the electric utilities, reactor manufacturers, and architect engineers, are in progress on an advanced standardized light water reactor. This work is sponsored by the Electric Power Research Institute. The simplifications used in the design of this reactor and the use of fewer and more reliable components are expected to reduce exposures considerably. The United States and Japan collaborated on the designs of advanced boiling water and pressurized water reactors. These reactors were designed to significantly reduce occupational exposures compared to present day nuclear plants. The total yearly collective dose for the advanced boiling water reactor, for example, is estimated to be on the order of only 50 person-rem compared to typical values of between 650 and 1000 person-rem for U.S. BWRs (Ref.2). The latest plant exposure data from Japan was used for this estimate and it was assumed that the latest technology to limit radiation build-up will be used. Some of the techniques used to reduce radiation exposure are discussed in section 4.5.

Excellent progress has been made in dose reduction both in the U.S. and other major nuclear countries. However, in order to insure implementation of the new techniques and equipment, plant managers are urged to establish plant-wide ALARA studies to provide appropriate evaluations and the setting of priorities schedules and budgets. Other recommendations are given in section 9.

2. INTRODUCTION

2.1 Background

Although occupational radiation exposures to individuals generally have been kept well below the regulatory limits in the United States (Ref.3), the collective occupational dose equivalents show large increases over time. Between 1969 and 1978 the annual collective dose rose gradually, at roughly the same rate as the total amount of electricity produced by nuclear power. After 1978, electricity generated by nuclear power was nearly constant for several years, but collective occupational dose increased steeply (Fig.1).

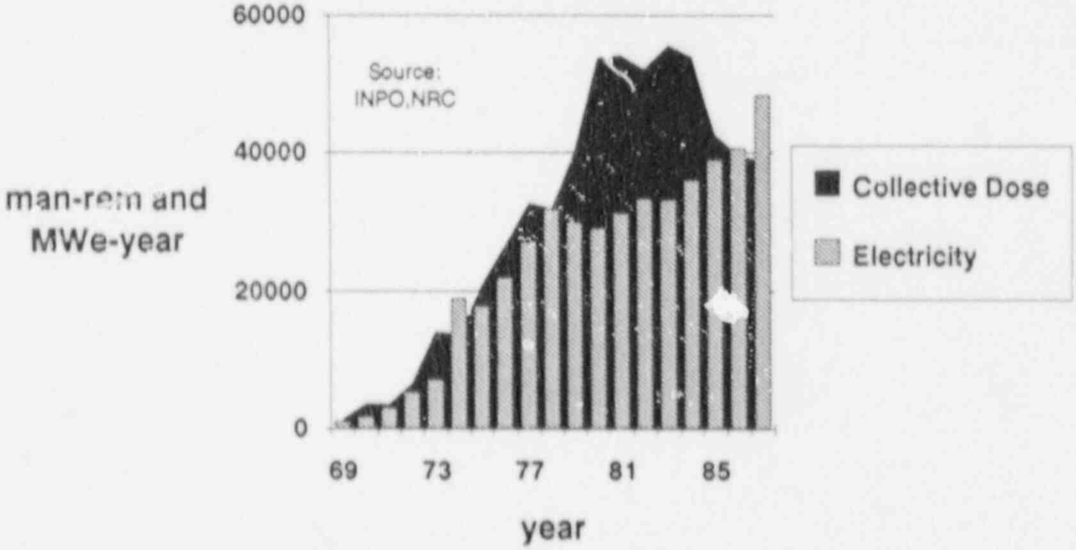
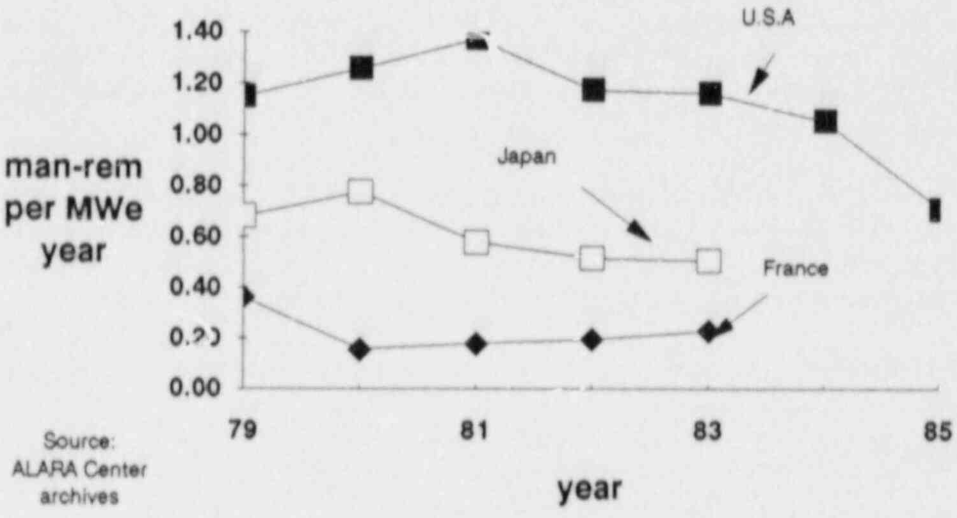


Figure 1- Collective occupational exposure compared with the gross electricity produced at U.S. nuclear power plants



Source: ALARA Center archives

Figure 2(a)-Collective dose equivalent per electricity unit for PWR plants of selected countries

The increase in occupational radiation exposure raised questions about ALARA (are doses as low as reasonably achievable?) since, compared to other countries with significant nuclear power generation, the collective occupational exposures were significantly higher in the United States, for example two to six times higher than in Canada, Sweden and France. Figures 2 and 3 show the collective occupational radiation exposure for several countries, normalized to electricity produced.

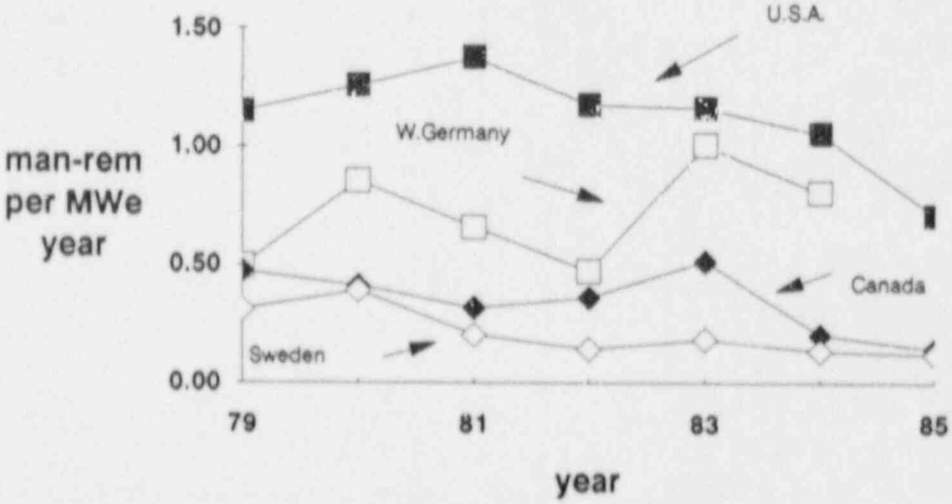
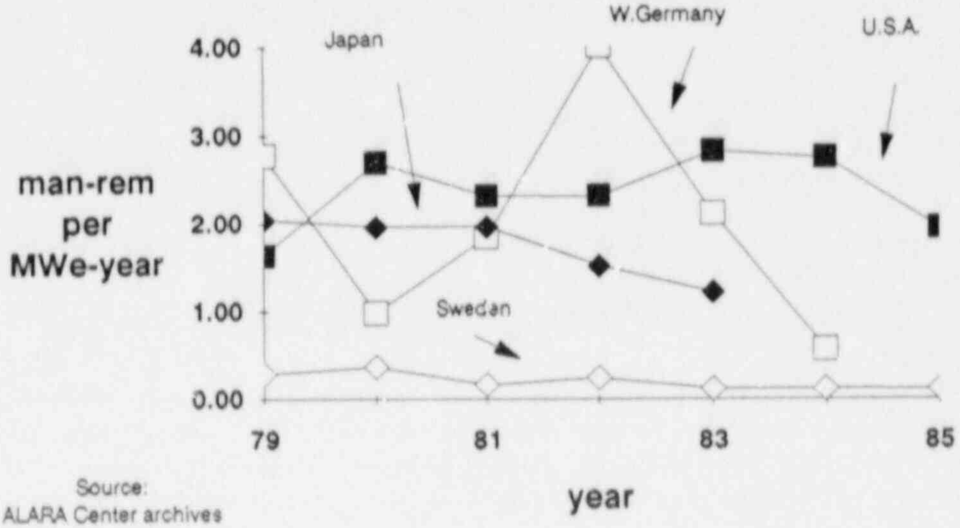


Figure 2(b)-Collective dose equivalent per electricity unit for PWR plants of selected countries

About 40% of the U.S. increase in the early 1980's could be attributed to NRC initiated multi-plant actions related to increased plant safety, that were required after the Three Mile Island 2 accident (Ref.4). Nevertheless the Nuclear Regulatory Commission (NRC) wanted to ascertain that appropriate efforts to reduce occupational radiation exposure in accordance with the ALARA principle were being made.

In compliance with its congressional mandate to oversee the radiation safety of operations personnel in nuclear power plants, the NRC asked scientists at the ALARA Center at Brookhaven National Laboratory to monitor and assess research underway in the United States and abroad that had potential to reduce occupational exposure.



Source:
ALARA Center archives

Figure 3-Collective dose equivalent per electricity unit for BWR plants of selected countries

To make the information readily available, a computerized data base was developed of worldwide information on dose-reduction research, and technological projects in health physics. The data base is continually updated, and summaries are provided to the NRC on a monthly basis and to contributors to the data base either upon phone request or by periodic (approximately annual) mailings. Presently there are about 220 research and 120 health physics technology projects in the data base. Information on these projects has been presented in two recent reports (Ref.5,6). In addition bibliographies of selected readings on occupational dose reduction and ALARA at nuclear power plants are periodically published (Ref.7,8,9).

2.2 Objectives of the Project

The objectives of this project were:-

- To monitor the status of research and development on dose reduction and health physics technology related to nuclear power.
- To inform the NRC about the efficacy of these activities.

- To make such information available to utilities, researchers and organizations.
- To exchange information on dose reduction with appropriate organizations here and abroad.

3. OCCUPATIONAL RADIATION EXPOSURE AT NUCLEAR POWER PLANTS

It may be appropriate to briefly review some fundamental questions before discussing what is being done and what needs to be done to reduce occupational radiation exposure. First, one should clearly comprehend why the reduction of occupational radiation exposure is desirable. Second, it is worth examining how the bulk of the occupational dose arises at nuclear power plants. Third, to make a better evaluation for the future, the direction in which the current dose trend is pointing should be examined. Apart from shedding light on why the effort to reduce dose is necessary and may even be profitable for the utilities, such a discussion provides answers to questions that have to do with how successful such an effort is likely to be. Is there a limit beyond which further effort loses any real meaning? Are we pursuing the objective by the best possible approaches? These and other questions are examined in the following sections.

3.1 Why is it Desirable to Reduce Occupational Radiation Exposure?

Increased occupational exposure impacts nuclear power plants in several ways, some more tangible than others. The first impact is on the health and welfare of the exposed personnel. The second impact, although not immediately obvious, is on the safety, reliability, efficiency and economics of plant operation. The third is related to the public's perception of radiation and its associated risks.

The risks to health involved with small radiation exposures over extended periods are difficult to quantify. The current regulatory limits on individual occupational exposures are believed to be safe compared to other "safe" industries (Ref.10), although these limits are likely to be reevaluated in the light of new and more accurate data. Utilities have kept the average annual dose per worker significantly below the NRC limits (Ref.3). It therefore seems that the present regulatory policies are sufficient to protect the health of workers so long as the current individual dose levels are maintained, although the low individual exposures have resulted in part from the large number of persons employed at each plant.

However, there are other very significant penalties involved with working in areas with enhanced radiation fields. The safety and reliable operation of nuclear power plants require extensive inspections and preventive maintenance. Since a number of inspection and maintenance tasks have to be performed in a radiation environment, work is more difficult and manpower-intensive than it would be in the absence of radiation (Ref.11).

To carry out the required tasks and maintain low individual exposures, the plant has to hire additional personnel. These personnel need advanced training in their special area of expertise and also some knowledge and understanding about how to work in a radiation environment. Moreover, substantial resources are required to provide other radiation protection services for plant personnel.

In addition, there are the inefficiencies and encumbrances of working in protective apparel, with gloves that reduce tactility, with respirators, and sometimes, with communications equipment. Dose limitations also reduce productivity because of the lack of continuity in tasks, as a result of changing the work teams. An attempt to quantify such inefficiencies is made in Reference 11.

To summarize, the penalties imposed by a radiation environment include: (a) the cost of the additional personnel required to keep individual exposures at an acceptable level, (b) the diminished productivity of workers in the radiation environment, (c) the cost of radiation protection services, (d) the cost of replacement power from the extension of reactor outages, and (e) the cost of handling the radioactive waste generated.

Work is in progress to extend the rated life of nuclear power plants. Any extension will add to the requirements for inspections and necessitate replacement of aging components in radiation areas. This should give an added incentive to the development of techniques to reduce occupational radiation exposure.

3.2 Main Contributors to Occupational Radiation Exposure at Nuclear Power Plants

Several factors contribute to increases in occupational radiation exposure at nuclear power plants (Ref.12). Among them are: (a) the activation and fission products that are deposited on out-of-core surfaces to produce radiation fields, (b) the additional maintenance and inspections required to service power plants as they age, and (c) the inspections, modifications and retrofits mandated or recommended to enhance plant safety.

Although there are a number of factors that affect occupational radiation exposure at water reactor power plants (Ref.12), there is evidence of a correlation between the intensity of radiation fields and collective occupational exposure (Ref.13,14). For pressurized water reactors, the strongest correlation is seen between the exposure rates in the channel heads of steam generators and the plant collective dose equivalent (Fig.4). The dose rates on the recirculation piping of boiling water reactors also appear to be correlated with the plant collective dose (Ref.14).

The chief cause for enhanced radiation fields is radiation produced by activation and fission products that are deposited on out-of-core surfaces, such as pipes, valves and pumps. The fission products, which result from failed fuel bundles, generally account for less than 10% of the out-of-core activity. With improved methods of fuel fabrication, better materials and advanced techniques to diagnose defective fuel, fission products are playing a diminishing role in the generation of out-of-core radiation fields, although industry plans to extend fuel cycles and increase burnups may reverse the downward trend.

The activation products result from the corrosion of materials in the primary system of the reactor. They are activated in the reactor core and later deposit on out-of-core surfaces. The main cause of the higher radiation fields is the nuclide cobalt-60. It has been estimated that the nuclide normally contributes about 80% to the plant dose from radiation sources (Ref.15). Cobalt-60 is produced by the neutron absorption of cobalt-59, the only isotope present in naturally occurring cobalt. Cobalt-59 occurs both as an impurity in the materials of reactor primary systems and as the major constituent in the hard facing alloys commonly used in components requiring outstanding resistance to wear. In PWR plants cobalt-58, formed from neutron bombardment of nickel-58, can also be a significant source.

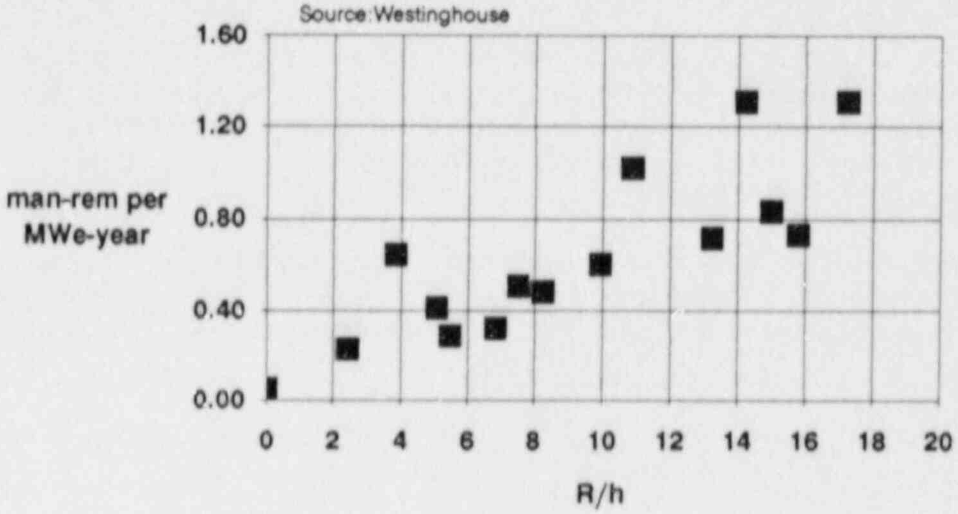


Figure 4 - Correlation of average steam generator channel head dose rates with plant collective doses at PWR plants

As nuclear power plants age, they require additional maintenance and inspections. Coupled with this are certain generic problems which increase occupational radiation exposure. For example, in recent years cracking of the piping in boiling water reactors caused by intergranular stress corrosion (IGSCC) has required a considerable amount of occupational dose for inspections and maintenance. In pressurized water reactors principal causes of occupational exposure were the problems associated with degradations in the tubing of steam generators which have required a large amount of repair or replacement work.

Finally, there have been a number of recently mandated or recommended requirements for backfits, inspections and modifications to enhance plant safety, which have had an adverse impact on occupational radiation exposure. For example, requirements for seismic upgrading, fire protection, and other mandated actions accounted for 40% of the occupational exposure at nuclear power plants between 1979 and 1983 (Ref.4).

3.3 The Trend in Occupational Radiation Exposure

Occupational radiation exposures hit their peak in the United States in 1980, when the annual collective occupational dose per reactor stood at 791 person-rem per unit-year (Ref.3). Since then there has been a continuing downward trend in occupational radiation exposure (Fig.5).

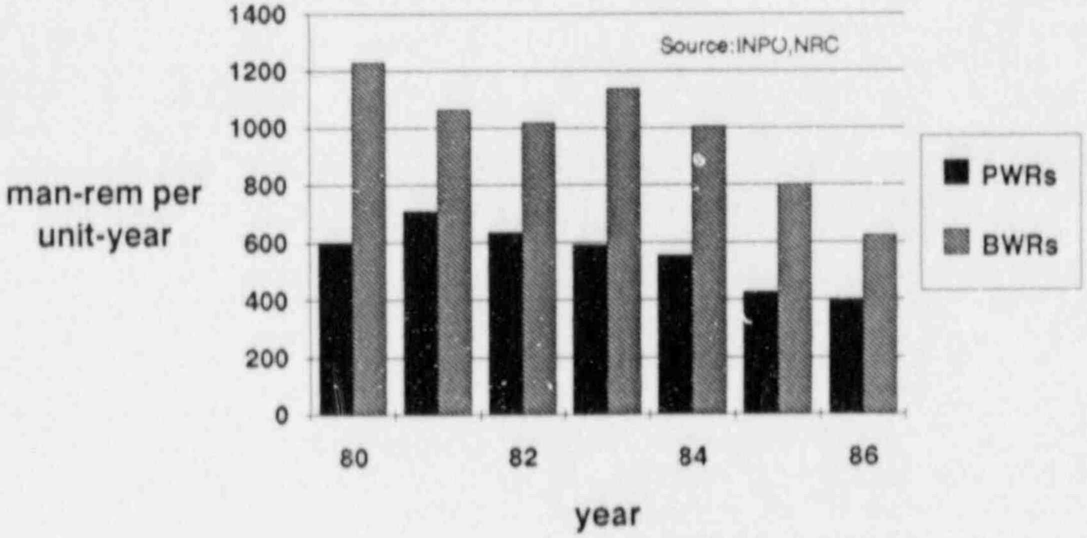


Figure 5 - Annual collective exposure per unit at U.S. light water reactors

Part of the downward trend is due to completion of many of the NRC-mandated safety actions, such as fire protection, seismic upgrading, etc. Also, a number of new plants have gone into service and these have had lower initial doses. Another reason is that the capacity factors, reflected by the equivalent availability (Fig.6), have tended to rise in the United States as the plants have matured and experience has been gained in operating them. Higher capacity factors generally have a positive effect on occupational radiation exposure because there is less maintenance required while a plant is operating and also access to radiation areas is more difficult during operation.

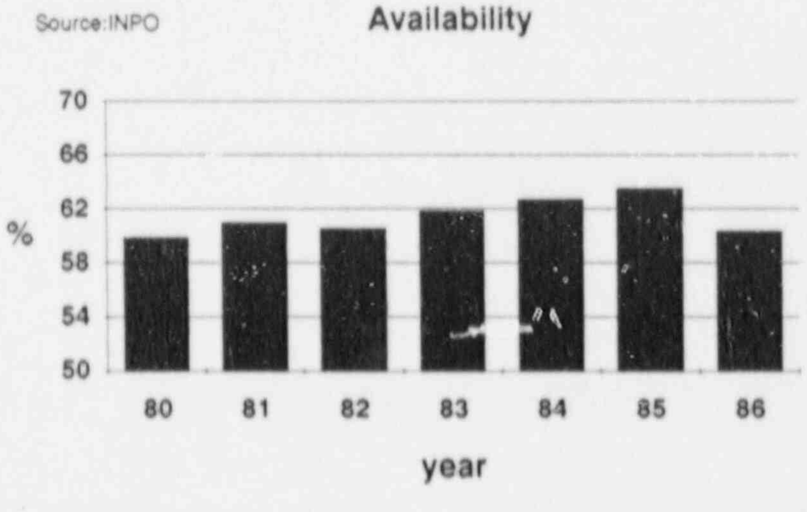
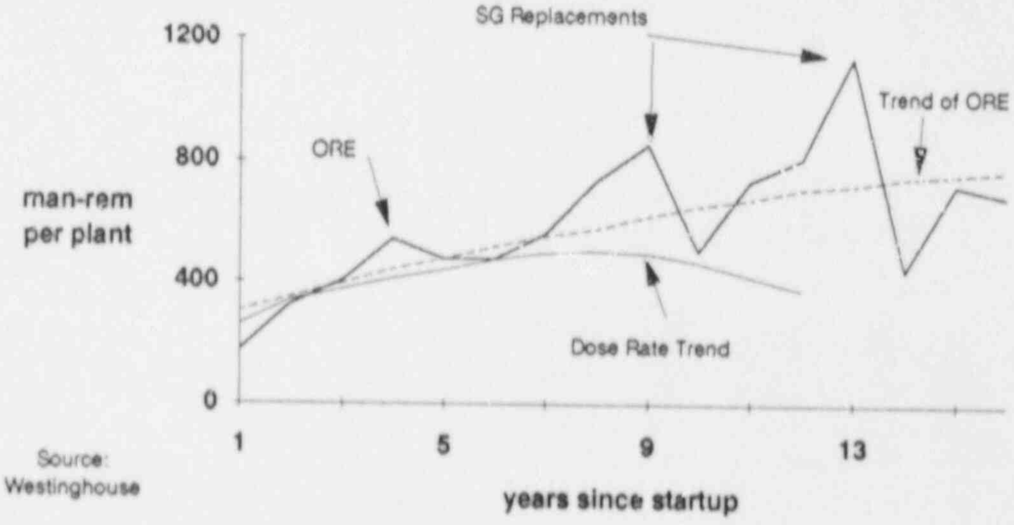


Figure 6 - Equivalent availability of U.S. commercial light water reactors as a percentage of their rated capacity

Moreover, research on dose reduction and health physics technology programs are finally having noticeable impact. Lessons learned from a number of dose-reduction projects are beginning to be applied, so that the downward trend in occupational radiation exposure probably should continue in the near future.

Despite the welcome decrease in occupational radiation exposure in the United States, when compared with other countries, the U.S. doses are still on the high side. However, even in countries such as France, with large numbers of new plants, the trend towards reduction in exposure appears to be flattening out (Fig.2). This may indicate that they have reached an ALARA plateau below which it is not cost effective to reduce exposure with the current nuclear reactor design and technology.

Further analysis has shown that the downward trend in occupational radiation exposure is not entirely unambiguous. For example, Westinghouse Electric Corporation has investigated collective dose equivalents at Westinghouse designed reactors for the NRC (Ref.16). Figure 7 displays the collective dose equivalents per reactor, as well as radiation levels, as a function of the number of years since the reactors have been in service. It is interesting to note that the radiation levels reach a broad peak for reactors in their 8th year of operation, after which they start to decrease. However the collective dose equivalents per reactor continue to rise. The higher doses for the older reactors, despite the decrease in the radiation levels, appear to be due to additional maintenance and inspections required as the reactors age. The reasons for the decrease in radiation levels for the older reactors are being investigated.



Source: Westinghouse

Figure 7 - Occupational radiation exposure summary for all Westinghouse power plants

4. CURRENT TRENDS IN DOSE-REDUCTION RESEARCH

To distinguish between the areas of research being carried out, and to identify their principal method of approach, we divided them into several broad categories. Sections 4.1 and 4.2 describe those approaches that reduce dose by reducing the radiation sources; Sections 4.3 and 4.4 consider research that decreases dose by decreasing the exposure time.

4.1 Research to Prevent Formation and Transport of Activated Corrosion Products

The principal techniques used to control contamination in the primary systems of nuclear plants are: (a) minimizing cobalt sources by reducing cobalt impurities in structural materials and by replacing hardfacing cobalt alloys, (b) preconditioning out-of-core surfaces to reduce production and release of corrosion products from these surfaces and to mitigate plating of activation and fission products onto them, and (c) using advanced water chemistry to control production, transport, deposition in the core, later and resuspension in the primary coolant of activated crud which can then be deposited outside the core.

4.1.1 Cobalt Reduction

Cobalt is present as a low-level impurity in structural materials of water reactors and at high levels in hardfacing alloys used for components which must resist wear. Estimates of the main sources of cobalt were made for pressurized and boiling water type reactors (Ref.17,18). The results are shown in Tables 4.1, 4.2, and 4.3.

Table 4.1. PWR Cobalt Sources

Source	Annual Release Rate per Plant (g/yr)
Steam generator tubing corrosion	33 to 55
Valve maintenance	10 to 30
Control rod drive mechanism wear	2 to 5
Check-valve wear	1
Gate-valve wear	0.5
Main coolant pump shaft wear	0.2

Source: Reference 17.

Table 4.2. Typical Cobalt Input In A Three Loop Westinghouse Plant

Major Component	Material	Cobalt Input g/year
Steam generator	Inconel 600	10.8
Fuel grid spacers	Inconel 718	0.4 to 2
Fuel assemblies	304 SS	3.2
RV internals and Piping	304 SS	10.4
Hard facing alloys	Stellite	12.9

Source: Reference 18

Table 4.3. BWR Cobalt Sources

Source	Annual Release Rate per Plant (g/yr)
Feedwater regulator valve wear	38 to 114
Valve maintenance	30 to 90
Control blade pin/roller wear	29
Cleanup discharge isolation valve wear	4
Main steam isolation valve wear	1.6
Feedwater swing check valve wear	0.4 to 0.7
Steam flow control valve wear	0.4
Feedwater pilot relief valve wear	0.06

Source: Reference 17.

In a 1982 study, Westinghouse Electric Corporation carried out a cost/benefit investigation to investigate the costs involved with the replacement of alloys which are likely to produce radioactive cobalt in PWR plants of their design. Based on this analysis they developed a set of priorities which are displayed in Table 4.4.

Table 4.4. Priority for the Replacement of Radioactive Cobalt Precursors for Operating Plants and those Under Construction

Component	Replacement Action	$/person-rem[1]	Rank
Control rod drive	Replace complete latch assembly	3,200	1
Main coolant pump	Replace complete rotating assembly and bearing cartridge	3,500	2
Valves, reactor coolant	Replace complete valve and all valves in system	8,100	3
Valves, loop stop	Replace complete valve and all valves in system	11,000	4
Valves, chemical volume & control	Replace complete valve and all valves in system	13,000	5
Steam generators	Replace steam generator and use low cobalt (0.015%) tubing	55,000	6

Source: Reference 18.

[1] Excluding outage costs

However, sources of cobalt which originate inside the reactor core make a much larger contribution to contamination than out-of-core sources, roughly by a ratio of 5 to 1 (Ref.19). This is so for two reasons. First, in-core cobalt sources spend more time in the high neutron flux of the core. Second, out-of-core sources have to be suspended in the coolant to be deposited inside the core, then activated, resuspended and finally deposited on out-of-core surfaces. Therefore it is of first importance to try to eliminate the in-core sources of cobalt.

Among the in-core sources in BWRs are the pins and rollers, and type 304 stainless steel tubing and sheathing of the control blades. In PWRs, inconel 718 fuel rod grid spacers, control rod cladding, and various fasteners comprise the main in-core sources. If the [illegible]WR in-core cobalt sources could be eliminated, a 30% reduction in component dose rates might be possible (Ref.20,21). Bergmann et al. have estimated that a 20% reduction in the exposure rate would result from the use of zircaloy instead of inconel grid spacers (Ref.18).

It is possible to specify an order-of-magnitude reduction in the amount of cobalt impurities in the materials selected for new nuclear power plants (Ref.14) or replacement components such as steam generators (Ref.22), pumps, and valves.. The cost of such a change would be small compared to the value of the potential dose savings. All utilities replacing steam generators are following this practice at the present time.

The replacement of the pins and rollers in the control blades of BWRs with low cobalt materials is attractive, since these are already replaced at regular intervals and the lessened radioactivity would also reduce their disposal costs. BWR control blades of new design have been tested in a commercial power plant (Ref.23). The pins and rollers for these blades were made from the low cobalt material Nitronic-60/CFA. As a result of work carried out by the Electric Power Research Institute and the General Electric Company all blades now being sold by GE are cobalt-free. Improved post-maintenance procedures are being developed which remove cobalt debris after the lapping and grinding of hardfaced valve seats (Ref.24). Replacement of cobalt-based hardfacing alloys is more difficult, since this requires the development of cobalt free substitutes. Work is in progress to find materials which would not sacrifice the high performance of cobalt-base alloys.

One significant success in this regard was the trial replacement of the Stellite hardfaced feedwater regulator valves at an operating BWR with valves based on Type 440C stainless steel. The performance of Type 440C stainless steel, which does not contain cobalt and nickel, was found to be outstanding for this application. After one year of service the valve wear was found to be 100 times less than that of the stellite hardfacing (Ref.17). In addition to eliminating a large source of cobalt, the use of stainless steel reduced the amount of valve maintenance required. Regulator valves have been replaced in several plants with valves containing non-stellite material as a result of these trials.

When cobalt-based valves require replacement, an alternate method to circumvent their use would be to adopt the approach used in Canada. The newer Canadian power plants rarely make use of cobalt-based, hard-faced alloys. Such alloys are only used in applications where their resistance to wear is essential. For the rest, valves with nickel-based alloys are utilized (Ref.25).

4.1.2 Preconditioning of Out-of-Core Surfaces

There are three objectives of preconditioning: (a) to reduce the amount of corrosion, (b) to mitigate the release of corrosion products to the coolant, and (c) to reduce the susceptibility of surfaces for the deposition of activated corrosion products.

When new reactor primary components are exposed to water they rapidly corrode. However, in due course an oxide film is formed which reduces corrosion considerably. For this reason, the preconditioning process is carried out during hot functional tests, before the reactor starts up. Preconditioning also is of importance in older plants where major components such as steam generators are being replaced.

Research is currently directed both to improving the processes for preconditioning the surfaces and to reducing the rate at which corrosion products deposit on the surfaces. Work is in progress to accelerate the oxidation rates during preconditioning to save critical-path time. Research being carried out to reduce the deposition rates of the corrosion products is directed in two main areas: (a) to prefilm the surfaces to reduce the tendency for oxide formation, and (b) to electropolish the surfaces to produce a smooth microstructure, on which the deposition of corrosion products is greatly reduced.

Initially it was feared that electropolishing would render materials more susceptible to cracking from intergranular stress corrosion. Recent work has shown that for both BWR and PWR components and chemistry this did not occur (Ref.14).

4.1.3 Advances in Water Chemistry

Control of water chemistry is one of the most cost-effective ways to reduce out-of-core radiation fields in PWRs and BWRs. In PWRs, prior to 1977, work was confined to optimizing the water quality during start-up and shutdown. During refueling shutdowns, air was introduced in the primary system, which increased the radioactivity in the coolant due to pH changes which led to dissolving of cobalt and nickel. The resulting high radiation fields caused delays in refueling activity. However, the release of the cobalt and nickel could be caused earlier by introducing hydrogen peroxide into the system, thus controlling the crud burst and allowing clean-up by the purification system.

Since 1977, use has been made of steady-state chemistry to minimize the formation of crud on the fuel and its transport to out-of-core surfaces. The technique involves controlling the formation of oxygen by operating at a constant pH of 6.9 and continuing to maintain an over pressure of hydrogen. Tests at operating nuclear power plants confirmed that such a regime reduced the amount of crud and significantly retarded the build-up of out-of-core radiation fields (Ref.26). More recently, research has indicated that even higher pH levels, around 7.4, would further reduce out-of-core radiation fields (Ref.27) Coordinated tests are in progress in the United States, F.R. Germany and Sweden to arrive at optimum pH values and to prove the reliability of reactor primary materials in the high lithium concentrations that are required for this PWR chemistry regime (Ref.6).

For BWR plants, it was shown that the presence of 5 to 15 ppb of zinc in reactor water inhibits the deposition of cobalt on stainless steel and thus reduces the build-up of cobalt-60 on piping surfaces by factors of 3 to 6.5 with normal water chemistry and about 20 with hydrogen water chemistry (Ref.28). The resultant reduction in radiation fields is significant.

Research has also shown that coating the piping with a film of zinc is not effective therefore a continuous or periodic zinc injection is required. The presence of zinc does not aggravate stress-corrosion cracking of primary system materials nor does it have a deleterious effect on the nuclear fuel. Radwaste production is also reduced to some extent. The intentional addition of zinc has now been qualified for BWRs. Zinc injection passivation is likely to be more important for older plants with high cobalt components.

4.2 Research to Remove Contamination

4.2.1 Decontamination

Chemical decontamination is one of the most cost-effective ways to reduce doses to occupational workers. At present, the most effective decontamination is carried out using dilute processes. A number of successful decontaminations of the recirculation piping systems of BWRs and steam generator channel heads in PWRs were carried out in recent years.

There are two main types of dilute decontamination processes. One type uses organic acids and chelating agents, sometimes adding corrosion inhibitors. The second type makes use of low-oxidation-state metal ions and does not require corrosion inhibitors. Both processes are mild and apparently have no adverse effect on reactor primary systems, if properly used. Initially the latter had the disadvantage of producing greater quantities of radioactive waste. However more recent research has succeeded not only in reducing the radwaste volume by half but also in shortening significantly the time required for decontamination (Ref.15).

Future objectives are to decontaminate the entire reactor primary system with or without the fuel in place. At present the latter appears to be the more cost-effective approach for PWRs. Full system decontamination with the fuel in place has the advantage of saving critical-path time, because decontamination can take place before the reactor vessel is opened, while the reactor is cooling down. It also reduces recontamination because the crud on the fuel is also removed.

However, it is necessary to establish that there is no adverse effect on the fuel and structural materials inside the reactor core from decontaminating the primary system with the fuel in place. Demonstrations are under way with the principal dilute decontamination processes to test this. Samples of fuel and materials from the Quad Cities Nuclear Power Plant, decontaminated using the LOMI and CAN-DECON processes are being destructively examined in hot cells (Ref 23). The longer term objective is to re-irradiate the decontaminated fuel in the core and reexamine it.

Non-chemical processes such as electropolishing, using rotating hones, steel brushes, and high pressure water and grit jetting also are proving to be effective decontamination techniques in appropriate circumstances. For example, activity deposited was reduced by a factor of over 400 in F.R. Germany by means of a special electropolishing process (Ref.29).

One area which needs continuing attention with chemical decontamination is in reducing the volume of radwaste generated and in diminishing the costs of disposal of the waste produced. This need is likely to increase as land-burial sites become less readily available and new regulatory requirements necessitate a reevaluation of the packaging, transportation and disposal procedures. Present research in this area is on reagent development to minimize resin requirements. Resin digestion or incineration may become economically attractive in the future.

4.2.2 Ultrafiltration

New filters are becoming available with acceptable flow rates and submicron mesh spacing. A significant fraction of activity in the coolant is from submicron sized particles. The small mesh filters apparently are able to better remove this activity. Ultrafine mesh filters have been successfully tested at the Obrigheim Power Station in F.R. Germany. The plant filters the primary coolant letdown, upstream of the demineralizer, with 0.45 micron absolute rated filters. Since inception of the program about 6 years ago the level of contaminants in the primary system.has been reduced by several orders of magnitude, and at the present time the system is so clean that a 0.45 micron filter lasts one year in service. During start-up and shut-down 1.2 micron filters are installed on the letdown to handle crud bursts (Ref.30).

Although there are operational differences between Obrigheim and U.S. PWR plants, the successful use of the fine mesh filters is worth exploring.

4.3 Research to Improve Reliability of Components

4.3.1 Improved Materials and Components

In recent years considerable progress was made in developing and qualifying better materials for nuclear power plants. Materials were developed that improve the reliability of components, make them less susceptible to corrosion, reduce their cobalt content significantly, or make them more amenable to decontamination.

For boiling water reactors materials such as nuclear grade 316 stainless steels have been qualified. These materials are not susceptible to intergranular stress corrosion cracking (IGSCC) during the normal operation of a BWR. Thus, for replacement piping and for the next generation of boiling water reactors, this chronic problem will be almost completely eliminated.

Stress corrosion cracking of steam generator tubes is also expected to be fully mitigated by the use of improved materials in new PWRs. More and more utilities are specifying use of these materials for replacement steam generators as well. Section 4.3.2 provides more details.

Development and qualification of substitutes for hardfacing alloys was discussed in section 4.1.1. As a result of this program feedwater regulator valves have been replaced in several BWR plants and the only control blades at present being marketed in the U.S. are cobalt-free.

Finally, improvements in the reliability of major components are allowing systems to be designed for significant dose savings. The design of reactor internal pumps for the advanced BWR is one such example (Ref.2).

4.3.2 Intergranular Stress Corrosion Cracking in Boiling Water Reactors

One of the most serious afflictions of BWRs in nearly all countries is the problem of cracking of the austenitic stainless steel piping from intergranular stress corrosion. This problem has resulted in the accumulation of large radiation doses during inspection, maintenance, and replacement of the pipes.

Intergranular stress corrosion cracking (IGSCC) was first encountered in BWRs in 1974: by 1979 over one hundred cracks were observed annually in BWR piping. The nuclear industry mounted a vigorous program to combat IGSCC by forming the BWR owners group to co-ordinate research efforts. The problem arises because some BWR materials, such as unstabilized austenitic stainless steels (e.g. types 304 and 316), lose some of their chromium content during pipe welding. These materials, thus sensitized, are susceptible to intergranular attack and, in some cases, may undergo stress corrosion cracking.

Fortunately, a number of materials and techniques were developed that can be used to overcome this major, dose intensive problem. Some techniques are suited to new plants and to plants where replacements are being considered; others are more applicable to operating plants. The techniques are based on three main approaches: to reduce the susceptibility of the material; to reduce the tensile stress level; and to improve the service environment.

4.3.2.1 Remedies to Reduce Susceptibility

To reduce the susceptibility to cracking, new materials such as nuclear grade types 316NG and 304NG stainless steel (SS) have been qualified, with tightly controlled requirements for carbon, nitrogen and cobalt. Grain size and degree of sensitization are also specified. Nuclear grade SS was specified for the piping of 17 domestic BWRs under construction and was used in a number of plants for piping repair and replacement. However, this remedy involves sizable expenditures in both dollars and dose for operating power plants. For example, replacing the recirculating system at the Nine Mile Point plant with type 316NG SS cost about $60 million. Other remedies developed, such as solution heat treatment and corrosion-resistant cladding, are less expensive but have other limitations.

4.3.2.2 Remedies to Reduce Stress

It was found that the residual tensile stress in welded piping can be made compressive by cooling the inside of the pipe with water during welding. Such cooling is also efficacious while the pipe is undergoing other outside surface treatments, such as induction heating. The remedies used to relieve the tensile stress of materials are based on this technique. They include heat-sink welding, last pass heat sink welding, and induction heating stress improvement (IHSI) (Ref.6).

IHSI was implemented in Japan in operating plants and those under construction. It is offered by several vendors in the United States at a cost of around $2 million for 100 welds. It proved to be very effective on uncracked pipe but provided only slight benefit on cracked pipe.

4.3.2.3 Remedies for Improving the Environment

The disadvantage of the stress- and sensitization-related remedies is that they are limited to the specific components on which they are applied. In contrast, the remedies related to the environment have the potential of protecting the whole coolant system. Accordingly, extensive efforts have been made to develop such remedies.

The process of radiolysis causes hydrogen and oxygen to separate from the reactor coolant while the reactor is in operation. Most of the hydrogen and oxygen is lost through the off-gas system, but approximately 200 ppb of oxygen and 15 ppb of hydrogen remain dissolved in the water. Deaeration during start-up seems to have a marginally beneficial effect. However, since the bulk of IGSCC occurs in the steady state, the effect of deaeration soon dissipates.

The use of conductivity control, by enhancing the purity of the feedwater, coupled with hydrogen water chemistry is a much more effective solution to the IGSCC problem. The feasibility of suppressing oxygen by injecting hydrogen into the feedwater (so-called hydrogen water chemistry) was demonstrated in the short-term in a Swedish BWR, and for longer periods at the Dresden-2 plant. Laboratory experiments in BWR conditions showed that, if the dissolved oxygen concentration is maintained at between 10 and 20 ppb, and the water conductivity is maintained below 0.3 æS/cm by maintaining high water quality, then IGSCC can be almost completely overcome (Ref.31).

Extensive efforts have been made to qualify hydrogen water chemistry for normal operation (Ref.31). The effect of this alternate chemistry on fuel cladding and other zircaloy core components was essentially benign, and there was no extensive formation of hydrides which would make the materials brittle. The process of zinc injection described in Sect.4.1.3, with its large potential to reduce radiation fields at BWRs, is even more effective in the hydrogen water chemistry environment.

The only adverse consequence of injecting hydrogen into the water appears to be its impact on radiation levels in the power plant and its environs. There is an increase in gamma activity of the steam, because hydrogen causes more of the N-16 produced in the core to partition to the vapor phase. The increases in annual dose from the enhanced radiation fields were evaluated for the Dresden plant (Ref.32). It is expected that the plant collective dose will increase by only 10 person-rem annually compared to an average annual collective plant dose at Dresden of 1935 person-rem (Ref.32). As regards dose to the public, the maximum exposure to an individual in the nearest residence (3 mrem/year) is small compared to the dose from natural background (80 mrem/year in the area). Certain other BWR plants may have an appreciably higher increase in their annual collective dose due to their poorer layout. Since the collective radiation exposure has been consistently higher for Dresden than the average for all BWR's, it may be worth investigating the additional person-rem consequences of hydrogen injection at a more representative power plant (Ref.33).

4.3.2.4 Improvements in Inspection Techniques

Cracking due to intergranular stress corrosion is much harder to detect than the commoner type of cracking caused by metal fatigue and requires an extensive inspection program. Even after mitigating actions for IGSCC, the requirements for in-service inspection increase. It is extremely important to carry out the inspections quickly and accurately because a large amount of dose results from them. Thus there was a research need to develop accurate techniques for in-service inspection of the piping which would result in relatively low occupational exposures.

Analytical techniques have been developed to predict leak rates from cracks. Acoustic emission is used to detect and locate leaks and to estimate their size. Completely automated inspection systems based on ultrasonics and transducers were developed to provide accurate information on the status of the piping especially as regards to IGSCC. MINAC(MINiature ACcelerator) high-energy radiography also is being qualified, and may be used to inspect those weld joints that are impossible to inspect with ultrasonics (Ref.6).

Almost as important as the development of better inspection techniques is the training of in-service inspectors. The Non-destructive Examination Center of the Electric Power Research Institute (EPRI) took a leading role in the program to evaluate and upgrade the training of in-service inspectors, and recently held round-robin tests of several inspection teams. The accuracy of the winning team from Switzerland's results demonstrated the precision of the inspection technique developed by the Swiss (Ref.6,34).

4.3.3 Steam Generator Tube Cracking in Pressurized Water Reactors

Of the numerous maladies that can afflict the steam generators of PWRs, perhaps primary water stress corrosion cracking of the tubes is the most pervasive. This problem, which has caused inordinate doses, generally arises on inside surfaces of mill-annealed, inconel-600 tubing that has been mechanically rolled into the tube sheet. The three factors that lead to steam generator tube stress corrosion cracking are material susceptibility, tensile stress, and aggressive environment.

To combat this problem research has been directed in several different channels, some more appropriate for new power plants or those replacing their steam generators, others more suited to improving the resistance to corrosion of existing equipment.

Research and development work in materials improvement has lead to the qualification of inconel-690, incalloy-800 and thermally treated inconel-600. All of these alloys are much less susceptible to stress corrosion cracking and other chronic steam generator problems. They may be specified to have a very low cobalt content. Thermally treated inconel-690 has been shown to be the most corrosion-resistant alloy for steam generator tubes (Ref.35).

For applications to existing steam generators, the processes of rotopeening and shot-peening are being extensively used (Ref.36). Both processes distribute, rather than relieve stress. Both may be accomplished remotely by automated tooling. The former process is faster but more suited for a non-radioactive environment, whereas the latter is more appropriate for operating plants. The occupational exposure for treating one steam generator in this way is generally close to 10 person-rem (Ref.36).

4.4 Research on Remote Systems

Robotics and remote systems are beginning to play an increasingly important role in the nuclear industry (Ref.37,38,39). Their use is especially important in hazardous situations or after accidents when high radiation fields are present. These devices were extensively used during the cleanup after the Chernobyl-4 accident, and they have played an important role in the decontamination of the TMI-2 power plant. They are now also used in more routine tasks to reduce personnel exposure, for example, in the decommissioning of the West Valley reprocessing plant (U.S) and in the maintenance of steam generators (Ref.6).

Some missions successfully conducted by robots include: decontamination and removal of contaminated surfaces, cutting and dismantling of structures and components, vacuuming, visual inspection, surveys of radiation levels, transporting radioactive material, packing radioactive waste material, manipulating valves, and using hand tools (Ref.40).

With the participation of the utilities, a Robot Users Group was formed in the United States in 1986 (Ref.41), comprised of engineers and scientists from the utilities, robot manufacturers, national laboratories, government organizations, academe, and service and consulting companies. The group brings together users, researchers, and robot manufacturers. Its objectives are to identify new applications, to propose the development of new equipment, and to assess the cost-benefit potentials of robotics technologies.

Remote systems technology can be subdivided into two main areas: remote tools and robotics (there is some overlap in these areas).

4.4.1 Remote Tools

There are a number of remote tools and devices in vogue at the present time that have proved their success at reducing occupational exposure and often critical-path time as well. The latter savings has enormous significance since it impacts strongly on replacement power costs.

Multistud tensioners presently are being used in most West German, French, and Belgian power plants. Despite problems caused from lack of standardization, they are beginning to be used in some US power plants. Their cost-effectiveness varies significantly from plant to plant. The manway covers on steam generators also are being removed remotely, thus saving considerable critical-path time and occupational exposure. Decontamination of the reactor cavity pool is being carried out quickly and efficiently at several utilities using commercially available equipment (Ref.42). Steam generator sleeving, plugging, peening, eddy current inspections, and other maintenance work are often done with robotics arms such as Westinghouse's ROSA, and SM-10W and Babcock & Wilcox's ROGER (Ref.6). In some cases, remote tools and robotics are being considered as an alternative to using decontamination procedures for controlling personnel exposure.

4.4.2 Robotics

The use of mobile robotics and teleoperator-controlled mobile devices is expanding in the nuclear industry. Not only do these devices save radiation exposure but they also increase plant safety by more frequent and better dose-free inspections. In addition they may make up for shortages in skilled man-power (Ref.43). At least 12 countries now produce robotics devices and a recent EPRI survey listed 95 types of robots, with many of them suitable for reactor work (Ref.40). The trend is towards making the manipulative and mobility functions of these devices more sophisticated and autonomous. At present, they can automatically enter and return from contaminated environments without human intervention. Repetitive manipulative tasks, such as smear sample acquisition, also are becoming automated (Ref.38,39).

Several devices are undergoing extensive tests in the field and are expected to be available soon on a full commercial basis (Ref.44). One interesting device, a six-legged robot named ROBIN (for Robotics INsect) is undergoing tests at the Savannah River Laboratory; it is especially suited to the complex environment of a typical nuclear plant. It is capable of easily changing directions, of climbing stairs, and of passing through narrow openings by changing its profile. Its telescoping arm can reach a maximum length of 5.5 ft. and support 50 lbs. The advantages of using legged locomotion include the ability to move over and get a stable foothold on almost any surface while maintaining a level and steady work platform. Its disadvantage is its expense which makes it suitable for only special jobs.

In another field test, at the Nine Mile 1 nuclear plant, a tracked robot named SURVEYOR was evaluated for two applications that were determined feasible with the available robotics technology (Ref.45). The untethered remote-control robot is equipped with a stereo-optic viewing system, with zoom capability, that greatly enhances depth perception. Moving at speeds up to 1 ft/s, it can climb stairs and travel through water 16 inches deep. SURVEYOR was used to perform inspection and surveillance of a radwaste building sump area. The robot system was found to be capable of close visual inspection of plant equipment, gages, valve positions, and line leaks, as well as of measuring radiation, temperature, and relative humidity levels. The radiation exposure necessary to obtain the data was 0.3 person-rem; without the use of SURVEYOR, it would have required 3 person-rem. However, in overall evaluations of routine, short duration inspections, it was found that the time involved with SURVEYOR outweighs any benefit from reducing exposure.

Another interesting device, the SURBOT (SURveillance roBOT), was developed for the NRC and has completed testing at the Browns Ferry nuclear power plant. The wheeled device was used to inspect and survey moisture separator rooms where exposure fields range between 500 and 5,000 mrem/hour and temperatures vary between 32 and 55 degrees Celsius. The projected annual savings were estimated to be 4,600 hours of labor, 3,000 sets of protective clothing and 108 person-rem of radiation exposure. The rated life of the device is 10 years and it is claimed that it amortizes its cost in about two years (Ref.44).

Robotics met the most extreme field conditions during the post-accident cleanup at Chernobyl. The experience showed that these devices are still some way from the kind of ruggedness and reliability necessary to operate in the kind of hostile environment presented at the Chernobyl site. The rubber tires on some robots bogged down in the asphalt roofs of adjacent reactor buildings during attempts to retrieve pieces of the destroyed reactor's graphite core. Operators had difficulty maneuvering some robots in narrow passageways, and sometimes the remote systems failed in the high radiation environment. In one case the batteries of the robot lasted only 20 minutes before they ran out of power, leaving the robot stranded in a highly radioactive zone (Ref.46).

Robotics are increasingly being used for special tasks at nuclear power plants. Some devices have undergone extensive tests and soon will be available commercially. Others are already available. The environment is altering very rapidly in the robotics industry and some devices are already beginning to be cost-effective even in routine tasks. However, the wide acceptance of robotics for routine tasks may still be some years away. Utilities are awaiting the development of rugged, multipurpose, field-tested devices that are easy to operate and maintain and are marketed at reasonable cost. In most cases this would imply that the cost of saving a person-rem should not exceed several thousand dollars.

4.5 Research on Advanced Reactor Designs

A national program is underway in the U.S to accelerate the evolution of nuclear technology by feeding 25 years of experience into the design of an advanced, simplified light water reactor (Ref.47). The program goal is to emerge within five years with the basic design of a standardized plant that is safer, lower in cost, and significantly lower in occupational exposure. This program is being sponsored by the Electric Power Research Institute.

The United States and Japan are also cooperating on the designs of advanced PWR- and BWR-type nuclear power plants (Ref.2,48). The advanced boiling water reactors and pressurized water reactors, which resulted from the long-term fruitful collaboration of the Japanese and U.S. nuclear industry, should see first operation by the middle of the next decade in Japan. Very large dose savings should be realized from these power plants which are based on two decades of experience in nuclear power plant design. Collective doses an order of magnitude lower than present day average doses are expected (Ref.2,49). At the same time, safety will be enhanced and costs reduced.

Westinghouse and Mitsubishi are collaborating on the design of an advanced PWR (Ref.49). One of their primary design objectives is reduction of occupational exposure to 100 person-rem/plant/year, compared to a 1987 average of 368 person-rem from existing PWRs in the U.S. This goal will be achieved using a number of proven techniques. For example, more space will be provided for maintenance and inspection tasks on the containment operating deck. The plant will have greater radiation shielding and improved access to all major equipment. A longer 24-month fuel cycle will be used compared to the present cycle of between 12 and 18 months. PWRs at present take about 30 days to refuel, with radiation exposures of about 32 person-rem. In the advanced PWR, with its integrated head and automated refueling equipment, refueling time should be reduced by about half and refueling exposure by about a factor of three.

Since repair of steam generators has been the largest single cause of occupational exposure in PWRs, those for the advanced PWR are being designed with special care. Besides the use of improved materials, these steam generators will have larger manways and channel heads, permanent hatch removal fixtures, and provisions for unmanned access. Very low cobalt materials have been specified for the tubing of the steam generators. Other sources of cobalt in valves, control rod drives, reactor internals, and other primary systems also are being minimized. In one Westinghouse concept, canned motor coolant pumps integrated with steam generator channel heads, and passive safety systems are being considered (Ref.49). These high reliability systems are expected to save a considerable amount of radiation dose due to reduced maintenance requirements and also to reductions in the sources of radiation.

Work on the design of an advanced boiling water reactor (ABWR) has been completed. This work resulted from a collaboration between General Electric of the United States and Hitachi, and Toshiba of Japan with guidance from the Tokyo Electric Power Company and other Japanese BWR utilities (Ref.2). The ABWR occupational radiation exposure has been estimated at 50 person-rem/year. It is expected to have a capacity factor of 86% and annual refueling and maintenance outages of only 45 days. It will be capable of some load following and will have plant safety enhanced by two orders of magnitude.

Among the major techniques planned to reduce occupational exposure in the ABWR will be the use of ten internal recirculation pumps located at the inside bottom of the reactor pressure vessel, which will eliminate the need for external loops and recirculation pipe nozzles. This will reduce radiation levels inside the containment by an estimated 50% compared with current plants and at the same time lower pumping requirements. The excess flow provided by the pump design will enhance plant operation and allow for full power operation with one pump out of service. Moreover, the internal pumps are of a wet motor design with no shaft seals. This provides increased reliability and reduced maintenance requirements and hence reduced occupational radiation exposure. Internal pumps have previously been used in Swedish and West German plants and have proven very effective in reducing occupational radiation exposure.

Anticipated in-service inspection needs have also been reduced by the elimination of recirculating pipe nozzles and the reduced amount of vessel welding during vessel fabrication. The reactor vessel was designed to permit maximum inspection of welds with automatic equipment. This will not only reduce exposure but also minimize manpower requirements.

The fine-motion control rod drives were especially designed for reduced maintenance needs and reduced radiation exposure. These drives utilize electric fine rod motion during normal operation and hydraulic pressure for scram insertion. Improvements and refinements in the design of the ball-screw assembly, the seal, and the drive supports improve maintainability and reduce maintenance requirements.

The use of minimum shuffle fuel loading schemes will reduce refueling times, while fuel burnup will be increased to higher values allowing for longer continuous operating cycles, lower fuel costs, and reduced occupational radiation exposure.

The radwaste handling facility designs have also been substantially improved. The use of pumped up heater drains, hollow fibre filters, and deep bed demineralizers without resin regeneration for condensate treatment will reduce liquid effluents. In the radwaste handling system, settling tanks will be replaced by hollow fibre filters and evaporation of the resin regeneration waste will be discontinued. Solid wastes will be handled by plastification or compaction. Spent resin and burnable wastes will be incinerated. With these improvements, the total radwaste volume of the plant is expected to be about 100 drums per year.

5. INTERNATIONAL RESEARCH ON DOSE REDUCTION

Considerable research on dose reduction and several very innovative programs of health physics technology are being carried out in a number of countries. This has contributed to very good performance in terms of collective dose reduction (Fig.2,3) and also resulted in enhanced capacity factors at power plants in those countries. As in the U.S., important research programs are ongoing abroad. The work in other countries is being closely coordinated with U.S. research, for example through EPRI agreements covering information exchange, joint projects, and presentations at technology transfer seminars. In this section promising research projects will be touched upon and particularly successful health physics programs which contribute some innovative features will be outlined.

5.1 Canada

Canada developed its own CANDU (CANadian Deuterium Uranium) reactors, and has a large development program which includes remote pressure tube replacement, water chemistry, and decontamination (Ref.5,6,50). Many of these techniques may be adapted to U.S reactors.

One interesting area of research, funded by EPRI, concerns pre-operational chemical cleaning of PWRs. In the usual hot-conditioning of pressurized water reactors a double-layered oxide film is formed. The first layer provides protection against corrosion but the second layer traps activity. In a project at the Chalk River Laboratories, film comprised only of the inner desirable layer was grown on stainless steels and Inconel. When the film was exposed to corrosion products, growth of the outer layer was inhibited (Ref.6,51).

In the area of robotics, the fueling machines of the CANDU reactors have earned an excellent reputation. They are designed to dispense fresh fuel bundles and remotely accept irradiated fuel while the reactors are operating at full power. This on-line refueling capability is largely responsible for the relatively high capacity factors of most CANDU-type reactors.

More recently, a program was undertaken to remotely replace the pressure tubes of certain CANDU reactors. The remote manipulation and control system for this task is being designed by SPAR Aerospace, a company which was also responsible for the space arm of the NASA space shuttle program. The objective of the Canadian project is to design a system which will carry out all the tasks with high hazards during the retubing operations (Ref.5). This indicates the level of sophistication of the Canadian industry in developing remote systems.

Another area where the Canadian program is of relevance is how radiation protection and contamination control are practiced during operations and maintenance. For example, all plant operations personnel are given a fairly advanced course in radiation control at Canadian power plants. Then they are made responsible for their own radiation protection and may designate contaminated areas, carry out radiation monitoring, fill out radiological work plans, etc. This saves both manpower and dose. Other details of Canadian practices are described in References 50 and 52

5.2 Federal Republic of Germany

There are several lessons to be learned from the experience in F.R. Germany. The chief ones are concerned with selection of proper materials. For example, the West German BWRs are the only ones immune from the problem of intergranular stress corrosion cracking (IGSCC) described above. The reason is primarily because they make use of type 347 niobium-stabilized austenitic stainless steel (Ref.6,48).

For PWRs, the Germans used Incoloy 800 in their steam generators (Ref.6). This material is highly resistant to cracking and can be specified to have very low cobalt content, both characteristics being highly desirable from the viewpoint of exposure reduction. Presently the West Germans are offering to replace steam generator tubes with Incoloy 800 tubes as a service to other countries (Ref.6). In performing this maintenance, they make use of fully automatic welding devices to reduce dose.

In a careful study they determined that one of the principal ways to reduce radiation fields at PWR plants is to use zircaloy instead of inconel fuel assembly spacers. The inconel spacers that have been in use have significant cobalt content, although the spacers being supplied at present are low in cobalt (Ref.53).

5.3 United Kingdom

The United Kingdom has a significant nuclear power program. However, their power reactors are mainly gas-cooled types that cause very low occupational doses. Their first PWR will be a Westinghouse reactor with advanced features such as better plant layout and low-cobalt materials. They have a significant research program on water reactors, some of it being sponsored by EPRI.

The British and EPRI cosponsored the development of the LOMI decontamination process, (Ref.6,54) that proved to be extremely gentle to BWR materials. Its modifications have also been successfully used on PWRs. The British, and the Canadians with their CAN-DECON process, are the only countries so far to carry out decontamination of the complete reactor primary system with the fuel in place. The results have been excellent, with typical decontamination factors of about 6 (Ref.55) and low resultant radiation fields. At the present time, the goal of the British decontamination program is to develop a decontamination process which leaves very little radioactive waste (Ref.55).

5.4 Sweden

An industrial team from the United States recently toured Sweden to evaluate their radiation control program (Ref.56). Among the factors that contributed to low personnel exposures at Swedish nuclear power plants were: (a) a strong managerial commitment, (b) plant design and modifications to reduce exposures, (c) good staffing, training, and work planning, (d) careful control of water chemistry, and (e) a favorable regulatory environment. References 12 and 57 also lead to similar conclusions.

The commitment of management at all levels is emphasized in a variety of ways. It is reflected in the design and operation of the power plants. Personnel exposures are discussed in the annual report and are a subject for oversight by corporate management. Goals are set and everyone at the plant, from the plant manager to the maintenance worker, has a responsibility to reduce occupational exposure. The regulatory agency seems more willing to consult and offer advice and is less adversarial than in the U.S. (Ref.57).

Some of the most significant contributions from Sweden in the area of dose reduction are in water chemistry (Ref.6,57,58). In PWRs they have been at the forefront of the thinking that operating at elevated pH for the primary coolant will reduce radiation fields significantly (Ref.58). A number of countries are beginning to follow this lead and the dose rates at the newest Swedish PWRs are a fine example of how much one can reduce radiation fields by operating with good water chemistry from the beginning. Dose rates at the channel heads of steam generators serve as a yardstick for radiation fields and doses at PWRs. Where typical radiation fields in channel heads in other countries are around 15 R/h, the newest Swedish reactors have fields of between 2 and 3 R/h.

5.5 France

The French made a major contribution to the technique of shot peening to inhibit corrosion cracking in steam generator tubes. The technique was initially used on the Belgian PWR, Doel 3. Since then over 270,000 tubes in 70 steam generators, four of which were American, have undergone this process. Since the first job at Doel, all the tools have been automated and now the entire operation can be monitored from outside the reactor building, using a semi-trailer which houses all the consoles and electronics required to control the robotized manipulator arms and other equipment used in the steam generator channel heads.

Recently Framatome developed a mobile vehicle, FRASTAR, for remote maintenance. This vehicle operates inside the containment of an operating reactor and in hazardous areas, such as the in-core instrumentation room after a thimble failure. In addition to inspections, it is designed to perform several specific maintenance activities (Ref.59).

One of the most interesting research avenues being pursued in France concerns the so-called 'soft approaches' to occupational exposure reduction. For example, in two projects at CEPN (Centre d'tude sur l'valuation de la protection dans le domaine nuclaire) dosimetric results from a number of countries are compared to determine the factors leading to high doses. Work planning, effective use of shielding,and other ways to reduce time in the radiation area or to reduce dose rates are examined in these projects.

5.6 Japan

Japan has one of the world's largest nuclear power programs. The first light water reactors built in Japan were imported and entered service in 1970. Since then, systematic and persistent efforts have resulted in the mastery of many of the afflictions of LWRs. In addition, the Japanese have made a concerted effort to introduce automation and robotics technology in their nuclear power program (Ref.60,61).

A focus for the Japanese efforts to improve LWR technology was provided by the LWR improvement and standardization program, initiated by the Japanese Ministry of International Trade and Industry (MITI), with the co-operation of the electric power companies and the reactor suppliers. The program has already had considerable success in improving the design of both BWR- and PWR-type plants. The BWR achievements include measures to overcome IGSCC, such as improvements in materials, welding technology,and operating procedures. It also includes measures to reduce radiation exposure, e.g. use of low-cobalt materials, techniques to reduce the amount of crud generated by use of better chemistry, and extremely leak-tight plants. The PWR improvements include enhancements in the reliability of steam generators, better spacers to prevent fuel rod bowing, automated eddy current testing, and automated inspection and repair of steam generator tubes.

Extensive use of automation in Japanese nuclear power plants is illustrated by the remote maintenance and inspection devices employed by the Tokyo Electric Power Company. These include: (a) automatic refueling platforms for refueling and shuffling, (b) automatic control rod drive handling machines, (c) semi-automatic tensioners for the head stud-bolts of reactor pressure vessels, (d) reactor cavity clean-up machines, (e) automatic ultrasonic inspection equipment for reactor pressure vessel shells; semi-automatic ultrasonic inspection equipment for piping, (f) main steam isolation valve automatic seat-lapping and handling equipment, and (g) semi-automatic overhauling and inspection equipment for control rod drives.

5.7 Finland

Although Finland is a small country, the program of radiation protection at the four power reactors in Finland is among the most efficient and it may be worth exploring some of the reasons for the success of their exposure control program. The Finns have limited the average annual collective dose at their power plants to less than 100 person-rem per reactor unit (Ref.6).

One factor which keeps occupational radiation exposure so low in Finland is related to the design features of their plants (Ref.62). The design of the plants is such that virtually no radiation doses are caused during normal operation. Radioactive systems are clearly separated from non-radioactive ones in different areas which are usually confined. The radioactive classification of each such area is displayed by a colored sign on the door. The rooms with higher dose rates are kept locked. A written permit is required for entry in rooms with dose rates above 100 mrem/h. This has typically kept personnel collective dose at 200 to 300 person-mrem per month during normal operations.

The finish of surfaces in their power plants are of high quality. All surfaces are painted with a hard surface epoxy paint so that no rough concrete can be seen. This makes the decontamination of the rooms quick and easy. Contamination levels exceeding 10^{-4} æCi/cm2 are not allowed even on protective overalls.

A significant cause of occupational radiation exposure at most PWR-type plants is work related to steam generator repair. In Finland each of the two PWRs has six steam generators of a different design than that adopted in most western countries. The steam generators are horizontally laid out, with horizontal tube bundles and hot and cold chambers formed as vertical cylinders in the middle of the steam generators. The primary coolant inlets and outlets are at the bottom and the manholes are on top. Each steam generator has 5536 tubes. During 18 years of operation with 12 steam generators only one leaking tube has required plugging. This tube leakage was caused by improperly rolling the tube into the tube sheet during the manufacturing process.

For radiation protection, real-time dosimeters with alarm are used in addition to thermoluminescent dosimeters. This makes it possible to control individual doses or collective doses for work teams on a daily basis. Apart from being an excellent measure to avoid overexposure, this procedure also aids in alerting plant management if doses for some jobs are increasing too rapidly so that they can take countermeasures in good time.

6. HEALTH PHYSICS TECHNOLOGY PROJECTS

There are a number of highly successful health physics technology programs in the United States and abroad (Ref.5,6). Utilities are developing dose-saving techniques and finding ways to carry out maintenance tasks rapidly and efficiently. In some projects 3-dimensional photography and videotapes are used as aids in teaching and in work preparation. The electronic (computer read) dosimetry and ubiquitous personal computers have made job specific dose tracking and maintenance of dose-records much easier. Correlations between plant dose and other plant operating parameters may be made and they are also being used for dose and work tracking (Ref.6). In addition, they open the possibility of utilizing such risk analysis programs as PC-TREE in the ALARA effort.

Projects on better shielding, advanced work planning, decontamination, robotics applications, training, improvements in procedure, and innovative ALARA incentives are described in references 5 and 6. The Scandinavians, for example, expect to reduce the duration of the scheduled outage period for their BWRs to 12 days by meticulous work planning (Ref.6). Such a reduction should have a very positive effect on occupational exposure. There is a joint project underway in Finland and Sweden to apply optimization of radiation protection at nuclear power plants. The impact of such factors as materials control, safety apparel, retrofits and other aspects of optimization have been investigated during this project (Ref.6). Two French projects which utilize "soft approaches" to reduce occupational exposure are described in section 5.5.

7. FUTURE DIRECTIONS

Some of the most significant or cost-effective approaches will be examined in this section and appropriate extrapolations made from them. The scope of the report will only permit the inclusion of broad areas which appear to be especially important.

For ease of discussion, the future directions have been divided into three: the short-term projects have essentially been proven and tested and are about to be applied; the "intermediate-term" projects are those which are still in the conceptual or research phases. The section on long-term directions looks at prospects for developments which are expected to produce results beyond the next decade.

In the short term, several projects are beginning to mature and will play an increasingly important role in saving occupational exposure. The dilute decontamination techniques now are sufficiently developed so that they are beginning to be used almost routinely in reducing radiation exposures at PWRs and, more especially, BWRs. Research is in progress to decontaminate the entire reactor primary system and it appears likely that processes will be qualified in the U.S. within two years. For BWRs the approach may be to do so with the fuel in place. For PWRs initially it may be done with the fuel removed. At least two countries have already been successful in decontaminating plants other than conventional LWRs with the fuel in place.

The techniques of shot-peening and roto-peening are essentially developed, as is their remote application. They are being applied to the steam generators of operating nuclear power plants and, more particularly, to plants about to go into operation where they are expected to be particularly effective and cost almost nothing in dose expenditure. These techniques are likely to avoid a considerable amount of radiation dose in steam generator repair and replacement.

Improvements in plant water chemistry have potential for large dose reductions and should prove particularly cost-effective. The EPRI/industry PWR water chemistry guidelines are now in force and are expected to have a moderate impact on occupational exposures at the newer PWRs and a lesser and more gradual impact on the older ones. For BWRs the use of zinc injection is likely to produce a significant reduction in radiation fields.

The many-sided attack on the problem of IGSCC at existing BWRs has also been successful. However, solutions such as corrosion resistant cladding and induction heating stress improvement (IHSI) modify only the welds to which these techniques are applied, leaving the rest of the piping system still susceptible to intergranular attack. Moreover, their use not only causes considerable occupational dose but is also fairly costly. The operational testing of hydrogen water chemistry will hopefully produce a remedy that will attack the problem as a whole and is also likely to be very cost-effective. The slight increase in occupational exposure due to the enhanced radiation fields from the use of hydrogen water chemistry is likely to be insignificant compared to the very large gains resulting from an increase in plant reliability and diminished needs for maintenance and replacement of the cracked piping.

Management personnel at operating nuclear power plants are well aware of the importance of cobalt in the radiation dose experience at their plants. Investigations are underway at a number of utilities to explore ways to replace cobalt components with ones which are essentially free of cobalt, for example, the control blades and certain high-cobalt valves in BWRs. It is also likely that the positive experience from the use of zircaloy fuel assembly spacers at certain PWRs will lead to these being specified at other PWRs in the future (Ref.63).

All these efforts will have a favorable impact on occupational dose control in the near term. Radiation exposures are expected to diminish significantly in some cases, though more often the radiation exposures will be contained or will decrease gradually. Thus, at power plants where these measures are introduced, there are likely to be no additional significant increases in collective occupational exposures. To reduce dose significantly at the older operating power plants is much more difficult than at the newer plants which have clean primary systems and where design changes can be put in place when they are most effective. Whether a power plant will be a high dose rate or low dose rate plant is essentially determined within the first few cycles (Ref.64).

In the intermediate term, improved construction materials for nuclear power plants should play a very important role in reducing occupational exposure and also in making the plants more reliable. Piping made from such materials as nuclear grade 304 and nuclear grade 316 stainless steels is not susceptible to IGSCC. Advanced steam generator tubing materials, like thermally treated Inconel-600 and alloys 800 and 690 are not only strongly corrosion resistant but can also be specified to contain very low quantities of cobalt. Cobalt-free substitutes for the hardfacing alloys in valves and other components and the newer zircaloy fuel assembly grid spacers for PWRs should eventually produce an appreciable reduction in occupational radiation exposure. Thus, for newer power plants, and also for those older plants where the primary piping, steam generators or other components are likely to be replaced, the new materials should result in better performing reactor primary systems.

In general considerable exposure reduction can result from the use of remote tooling although some of the devices have yet to be proven effective and in some cases their cost-effectiveness is dependent on plant related circumstances (Ref.1). Multistud tensioner devices for reactor pressure vessels are becoming more widely used, as are devices to remotely remove the manway covers of steam generators. Integrated reactor pressure vessel head assemblies are now offered for some new plants. A considerable amount of steam generator work is possible using remote tooling, and remote tooling design is improving at a brisk pace. For certain types of decontamination operations, remote or automated machinery is beginning to save person-rem and, in some cases, important critical-path time (Ref.42).

Robotics are being considered for some applications: their use should become more routine in the next decade as rugged, easily maintained, and cheaper robotics systems become available. Even in routine surveillance their use is approaching cost-effectiveness, and they are already saving several times their cost in particular high-hazard situations.

Significant strides have been made in the design of plant layout and also in shielding. The newer plants are more likely to be oriented to human factors and to enabling maintenance to be carried out much more easily in considerably less time. Moreover, designers now appreciate that a simple system, with few but high quality and reliable components, needs much less maintenance and so rapidly pays for itself (Ref.65). Simpler reactor systems are now offered by the major vendors.

In the long term, one must look to the designs of advanced light water reactors (LWRs), the high temperature gas-cooled reactor (HTGR), or perhaps the liquid metal reactor (LMR) for a significant reduction in occupational exposure. A discussion of the design developments in the area of dose reduction for the advanced PWRs and BWRs is given in section 4.5. The non-LWR type reactors are outside the scope of this report.

8. CONCLUSIONS

Despite the vicissitudes that the nuclear industry is going through in the U.S. and abroad, its research and development profile remains in a healthy state. The doldrums that supposedly afflict the nuclear industry are not perceptible in R & D as may be observed by examining the vigorous research program in the area of dose-reduction that already is producing significant results.

The achievements of nuclear power in dose-reduction research are many, and are beginning to be felt in such areas as the development of improved materials, in water chemistry, in decontamination, and in remote tooling. The chronic problems of intergranular stress corrosion cracking in boiling water reactors and steam generator tube cracking in pressurized water reactors largely have been solved. The foundation of a nuclear robotics industry is being laid. Significant strides are also being made in the area of health physics technology.

The bulk of this work is being carried out by the nuclear industry itself: by the utilities, nuclear steam system suppliers, and smaller support companies. Often the research effort is sponsored by such industrial umbrella organizations as the Electric Power Research Institute (EPRI), the Empire State Electric Energy Research Corporation (ESEERCO), and the Nuclear Management and Resources Council (NUMARC). In other countries, the research is sometimes carried out under the aegis of government agencies such as the Ministry of International Trade and Industry (MITI) in Japan.

Since the events at Chernobyl, the international nuclear community has become particularly conscious of the importance of radiation protection. At the meeting organized by the International Atomic Energy Agency (IAEA) to review the events at Chernobyl, one of the principal recommendations was to strengthen radiation protection at nuclear power plants (Ref.66). The Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) is also pursuing this objective. Scientists at the BNL ALARA Center will collaborate with these and other appropriate organizations in radiation protection and ALARA at nuclear power plants, so that information can be exchanged and research efforts shared. The systematic accumulation of information on radiation protection from other countries cannot but help benefit the nuclear industry's dose-reduction efforts.

It may ultimately be possible to achieve such low individual and collective doses that they become an insignificant factor in the workers' health and welfare. The goal in the Scandinavian countries, for example, is to restrict almost all radiation sources to the reactor core where they belong, with the very small remaining proportion confined to the rest of the reactor primary system. They tolerate very little contamination and only low dose rates outside the reactor primary system. Their plants are clean and free of contamination so that workers can carry out most of their operational tasks in normal attire. This kind of environment in U.S. plants will help to reduce the public's perception of "the radiation hazard issue" as an argument against nuclear power by making work in power plants almost conventional. In addition, and just as important, it will make the plants much more efficient and economical to operate.

Already the targets for low collective dose for the advanced nuclear plants now being designed are approaching the objective outlined above. Some power plants in the U.S and abroad are showing, by their efficient low-dose operation, that it is a realistic goal. Big improvements have been seen in some old plants. However, only with major efforts at dose-reduction can some of the older power plants, with their high-dose characteristics, be gradually improved. Thus, the full realization of this goal may only be possible sometime in the next century.

9. RECOMMENDATIONS

In order to continue to rapidly reduce occupational radiation exposure a continuing coordinated effort is required between the NRC ,the licensees, industry umbrella organizations such as EPRI and INPO, the reactor steam supply system vendors ,other engineering companies concerned, and the ALARA Center.

Recommendations for continued improvement are:

Cobalt Removal: In general, higher priority should be given to removing cobalt from the in-core materials. This would reduce radiation dose considerably and at much lower cost, since most of the materials in question require periodic replacement. For PWRs, this would involve replacing inconel 718 fuel rod grid spacers with zircaloy spacers which have essentially no cobalt content. The inconel 625 control rod cladding also should be replaced. In BWRs, control rod pins and rollers and type 304 stainless steel tubing and sheathing of control blades are also good candidates for early replacement with materials containing low cobalt, and indeed have been replaced in a number of plants.

Some out-of-core primary components also release significant amounts of cobalt and are appropriate candidates for early replacement. Among these are, for PWRs the control rod drive mechanism latches and the charging systems valves; for BWRs the feed water regulator valves, and to a lesser extent, the main steam isolator valves.

Preconditioning: (a) Priority should be given to developing processes to precondition surfaces prior to installation both for replacements and new plants. This approach would produce significant savings in critical-path time. (b) Additional attention should be given to improvements in prefilming processes. An example of a new approach to prefilming, being developed in Canada with EPRI funding, is given in section 4.1.

Decontamination: (a) A concerted effort should be made to move to a regime of periodic decontamination of the full primary system with the fuel in place, particularly for BWRs. Considerable savings in critical-path time would result since decontamination would be possible before the pressure vessel head is removed and while the reactor is cooling. (b) Efforts should also be made to develop decontamination processes that generate very little radioactive waste. Some work is being done in the U.K. and Sweden where suitable candidate processes which produce low radwaste by volume are being examined. (c) Some research should be channeled towards investigating the possibility and technical feasibility of on-line decontamination processes. Such approaches will provide significant savings in radiation dose and in critical-path time.

Water Chemistry and Purification: For BWRs, appropriate plants should investigate the implementation of the now qualified process of zinc injection to reduce dose rates. For PWRs, fuel vendors should expedite studies into the qualification of increased pH chemistry for use in power plants which utilize fuel of their manufacture.The use of submicron filters to remove crud from the primary system of PWR type plants should be investigated. If a strong reduction in activity is feasible under operational conditions then the optimum conditions for their use should be established, including the appropriate chemistry.

Non-engineering approaches: More attention should be given to non-engineering approaches to dose reduction. Among these would be; improvements in contamination control, work planning, training, innovative use of mock ups, photography, video, as well as other new ALARA approaches. Novel techniques and procedures should be collected, evaluated, and disseminated to the utilities. For example, a project is underway in France to compare the work practices of several European plants for a specific high dose job (Ref.6). The cost of such non-engineering approaches is small compared to the benefits that they provide.

One of the most effective ways to reduce collective dose is to reduce the scope or frequency of work in radiation areas. In this regard optimization studies are needed for backfits, modifications and current surveillance requirements. An example was discussed in Reference 67, where the optimum time frame for steam generator tube inspections was shown to be once every five years, not every year. Research in such areas is likely to be very fruitful in reducing the length of U.S. plant outages and occupational radiation exposure.

Management and Planning: In order to assure a well established and smoothly functioning ALARA program, the managements of the utilities and the power plants need to emphasize their interest in and commitment to ALARA. This may be done, for example, by developing strong and forceful ALARA organizations at power plants, by requiring plant-wide ALARA "plans", by creating various incentives, and by requiring periodic reporting on ALARA performance to the highest levels of management.

The plant-wide ALARA plans should include comprehensive evaluations of potentials for dose reduction and long-term benefits and be based on cost-effectiveness and optimization considerations. They should outline what needs to be done, set priorities, and establish target dates and budgets. Such plans should be reviewed and updated periodically (e.g. annually).

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